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TECHNICAL NOTES

# Embrittlement of Rotor Materials for use on Hydrogen

Hydrogen embrittlement involves the ingress of hydrogen into a component, which can seriously reduce the ductility and load-bearing capacity, cause cracking and catastrophic brittle failures at stresses below the yield stress of susceptible materials. Hydrogen embrittlement does not affect all metallic materials equally. The most vulnerable are high-strength steels, titanium alloys and aluminum alloys.

The following chart, published in NASA Technical Memorandum X-68088, lists materials in order of decreasing susceptibility at room temperature:

TABLE II. - METALS AND ALLOYS EMBRITTLED BY HYDROGEN

| Hydrogen environment embrittlement[a,b] | Internal reversible hydrogen embrittlement[a,c] | Hydrogen reaction embrittlement |
|---|---|---|
| High strength steels<br>18Ni Maraging<br>410, 440C, 430F<br>H-11, 4140, 1042 (Q&T)<br>Fe-9Ni-4Co, 17-7PH | High strength steels<br>4340, 4140, H-11<br>17-4PH, AM 355<br>18Ni Maraging<br>E8740, 17-7PH | 1. Hydride embrittlement ($MH_x$)<br>(a) H reacts with matrix<br>Ti, Zr, Hf, V, Nb, Ta<br>Mn, Ni, Pd, U, Pu, Th<br>Rare earths<br>Alkalines<br>Alkaline earths |
| Nickel and nickel alloys<br>Electroformed Ni<br>Nickel 200, 270<br>Inconel 625, 700, 706, 718<br>Rene 41, Hastelloy X<br>Udimet 700, Waspaloy<br>MAR M-200DS, IN 100 | Exp. Fe-Ni-Cr alloys<br>Exp. Fe-Cu alloys | (b) H reacts with element in matrix<br>MgZr, MgTh alloys<br>2. High pressure gas bubbles |
| Low strength steels<br>Armco iron, CK22, CK45, 1020<br>1042 Nor., HY-80, HY-100<br>A-302, A-515, A-517<br>Titanium alloys<br>Ti-6Al-4V, Ti-5Al-2.5Sn | Ti, Zr, V, Nb, Ta<br>Cr, Mo, W, Co, Ni<br>Pt, Cu, Au, Al, Mg<br>and/or some of<br>their alloys | (a) H reacts with itself ($H_2$)<br>Steels, OFHC Cu<br>Ni, Al, Mg, Be<br>(b) H reacts with foreign element in matrix<br>$CH_4$ -- low alloy steels, Ni alloys<br>$H_2O$ -- welded steels, Cu, Ni, Ag |
| Cobalt alloys<br>HS-188, L-605, S-816<br>Metastable stainless steels<br>304L, 305, 310<br>K-Monel<br>Be-Cu Alloy 25<br>Pure titanium | Metastable stainless steels<br>304L, 310<br>K-Monel | |
| Stable stainless steels<br>316, 321, 347, A-286<br>Armco 21-6-9 | High strength nickel alloys<br>Inconel 718<br>Rene 41<br>Waspaloy | |
| Copper alloys, OFHC Cu<br>Aluminum alloys<br>1100, 2219, 6061, 7039, 7075 | Stable austenitic steels<br>316, A-286, U-212 | |

[a] Listed in approximate order of decreasing susceptibility at room temperature.
[b] Most alloys from Refs. 14 and 23.
[c] Most steels and nickel-base alloys from Ref. 26.

For approximately 30 years, Hoffer Flow Controls has recommended and used the Nickel 200 rotor for liquid hydrogen applications. There have been no reported failures of a Nickel 200 rotor used in liquid hydrogen applications during that time. Possible reasons for this include:

1. Nickel 200 is less susceptible to embrittlement than 17-4 PH, likely because it is a softer, more ductile metal.

2. The severity of hydrogen embrittlement is a function of temperature and appears to be less of a concern for liquid hydrogen applications due to a lower permeation rate.

3. The load on the rotor may not be significant enough to result in catastrophic failures, even if there is internal cracking and fracturing due to hydrogen ingress.

Steel with an ultimate tensile strength of less than 1000 MPa (~145,000 psi) or hardness of less than 32 HRC is not generally considered susceptible to hydrogen embrittlement. As the strength of steels increases, the fracture toughness decreases, so the likelihood that hydrogen embrittlement will lead to fracture increases. In high-strength steels, anything above a hardness of HRC 32 may be susceptible to early hydrogen cracking and may also experience long-term failures anytime from weeks to decades after being placed in service due to accumulation of hydrogen over time.

The key to reducing susceptibility to hydrogen embrittlement appears to be the use of soft, ductile metals. Annealing may be used to further reduce hardness and increase ductility.

The following table is an analysis from material certs for three common metals used for rotors: 17-4 PH SS, Super Duplex SS and Nickel 200.

| **Lot#** | **Description** | **Hardness (HRC)** | **Hardness (HB)** | ***ROA %** | **Elongation%** |
|---|---|---|---|---|---|
| | | Rockwell | Brinell | | |
| ***Nickel 200 (UNS N02200)*** | | | | | |
| H181631MD | Heat: 166225, annealed 900°C / 2H / air | <10 | 120 | 75 | 51 |
| H21743MD | Annealed 1202° F / 4H / air | <10 | 95-99 | 87 | 59 |
| | | | | | |
| ***Super Duplex SS*** | | | | | |
| H171279M | **UNS S32760** - Heat: A14587, solution annealed 1100°C/ 0.5H /water | 22-23 | 240 | 76-79 | 39-42 |
| H21603MD | **UNS S32750** – Solution annealed, 1100°C/ 3.5H /water | 24 | 250 | 75-82 | 38-43 |
| ***17-4 PH SS (UNS S17400)*** | | | | | |
| H21421MD | H900 1900F / 1 hour / air cool | 34 | 320 | 45.1 | 14.5 |
| H18532MD | H900 L, Heat: 698X | 43 | 400 | 54.11 | 14.0 |

* Reduction of area

**Conclusion:** The information in this report suggests that the top choice of rotor material for both gas and liquid hydrogen applications would be **Nickel 200.** It has long been known that variable reluctance (mag) sensors work well due to the magnetic properties of Nickel 200. In April of 2022, extensive testing was performed to determine the sensing capabilities of an amplified RF sensor and Nickel 200 rotor.

The RPR pickup was tested in a 1” flowmeter over the entire flow range and operating temperature range of -40°C to 85°C. Based on the results of this testing, the RPR pickup is recommended for all hydrogen gas applications requiring an RF flow sensor and Nickel 200 rotor.